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Holeva

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[54] **METHOD AND APPARATUS FOR PASSIVE AUTORANGING USING RELAXATION**

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[51] **Int. Cl.**[5] **G06K 9/00; G06K 9/36**

[52] **U.S. Cl.** **382/8**; 382/41

[58] **Field of Search** 382/1, 8, 41, 43; 358/227; 354/400, 402; 250/201.2, 201.7

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Primary Examiner—Joseph Mancuso
Assistant Examiner—David Fox
Attorney, Agent, or Firm—Steve Mendelsohn; William H. Murray

[57] **ABSTRACT**

A method and apparatus for passive autoranging. Two cameras having different image parameters (e.g., focal gradients) generate two images of the same scene. A relaxation procedure is performed using the two images as inputs to generate a blur spread. The blur spread may then be used to calculate the range of at least one object in the scene. In one preferred embodiment, a temporal relaxation procedure is employed to focus a third camera. In another preferred embodiment, a spatial relaxation procedure is employed to determine the range of a plurality of objects.

89 Claims, 7 Drawing Sheets

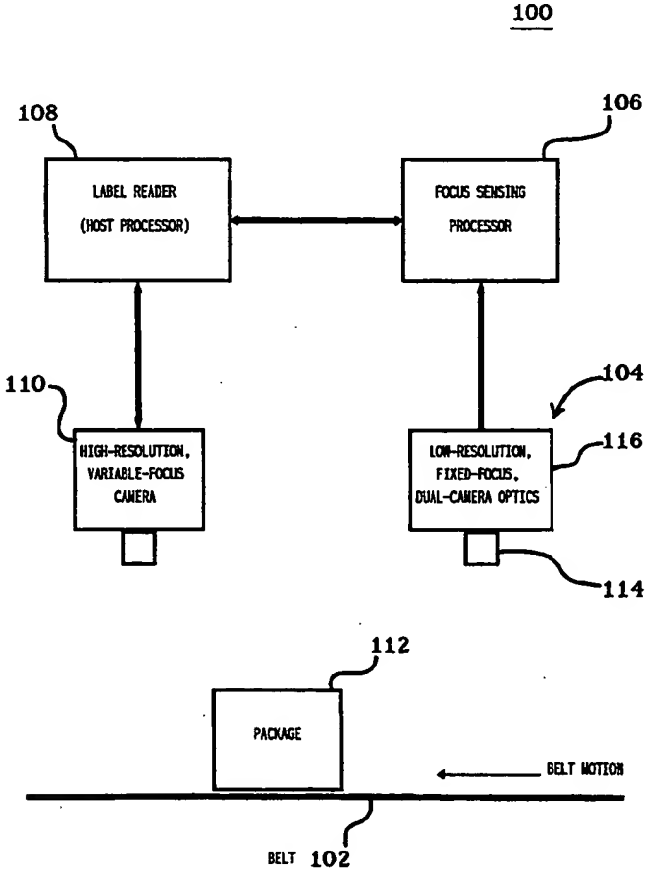


FIGURE 1.

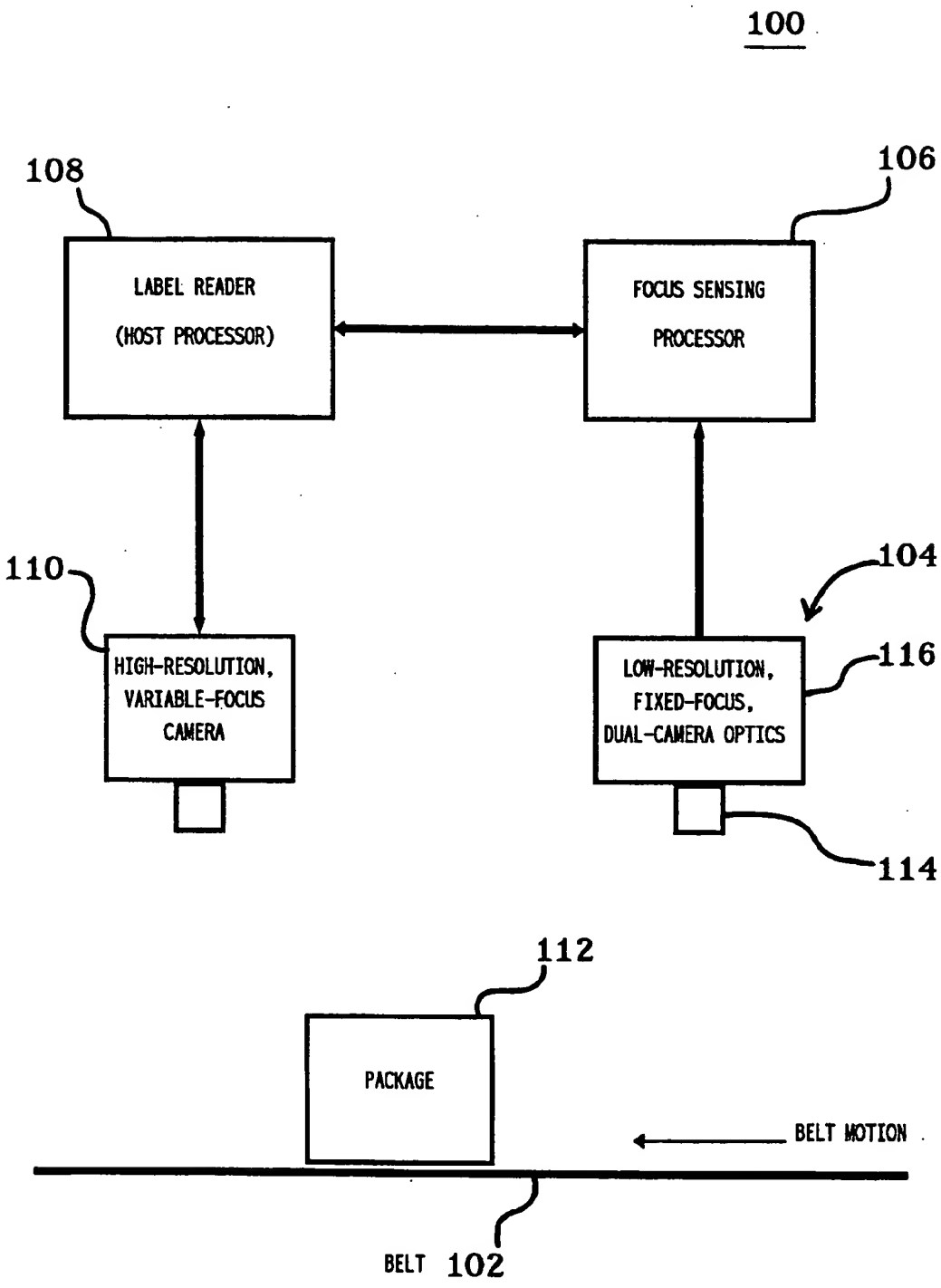

100
108
106
LABEL READER
(HOST PROCESSOR)
FOCUS SENSING
PROCESSOR
110
104
HIGH-RESOLUTION,
VARIABLE-FOCUS
CAMERA
LOW-RESOLUTION,
FIXED-FOCUS,
DUAL-CAMERA OPTICS
116
114
112
PACKAGE
BELT MOTION
BELT 102

FIGURE 2.

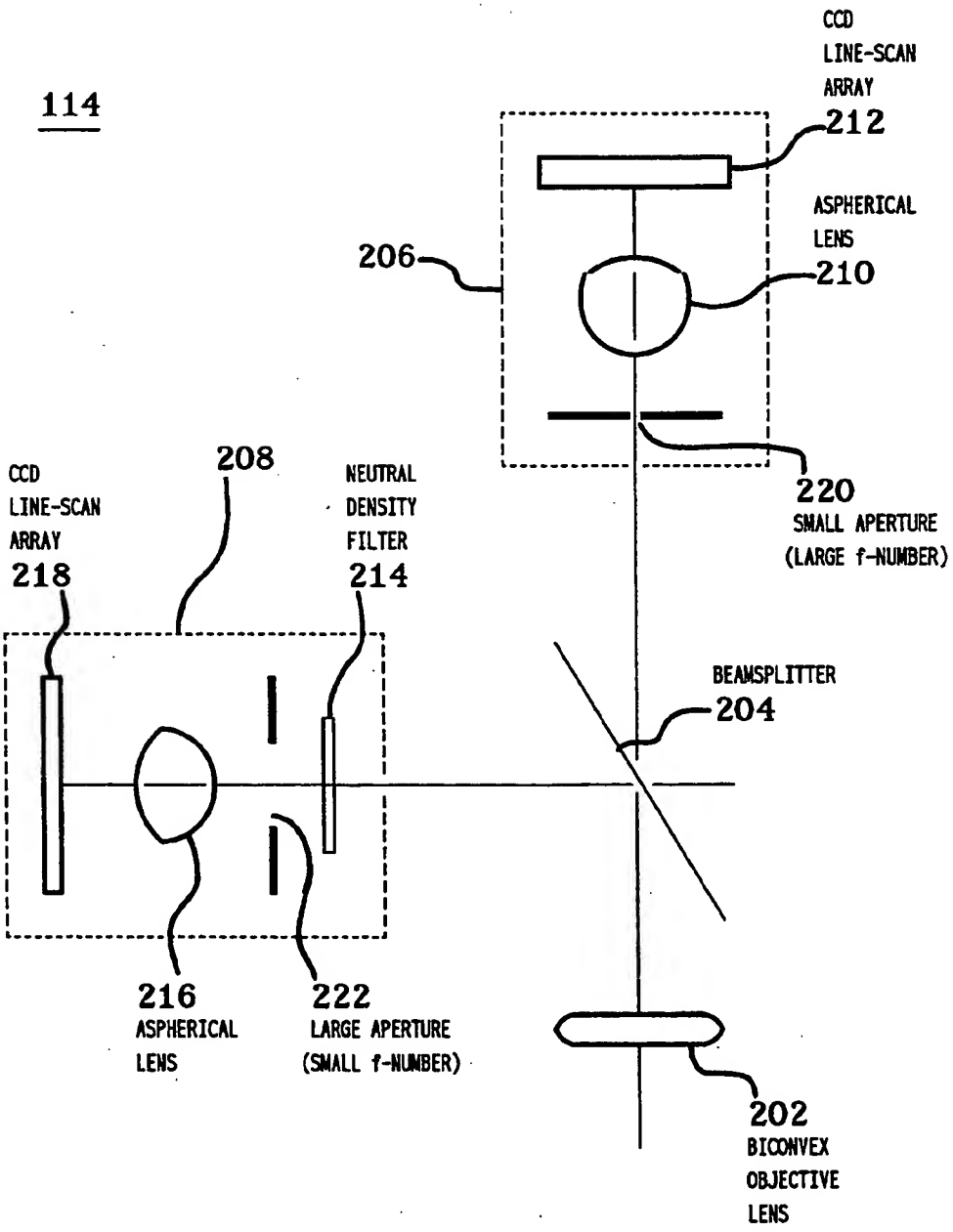

114
CCD
LINE-SCAN
ARRAY
212
ASPHERICAL
LENS
210
206
220
SMALL APERTURE
(LARGE f-NUMBER)
208
CCD
LINE-SCAN
ARRAY
218
NEUTRAL
DENSITY
FILTER
214
BEAMSPLITTER
204
216
ASPHERICAL
LENS
222
LARGE APERTURE
(SMALL f-NUMBER)
202
BICONVEX
OBJECTIVE
LENS

FIGURE 3.

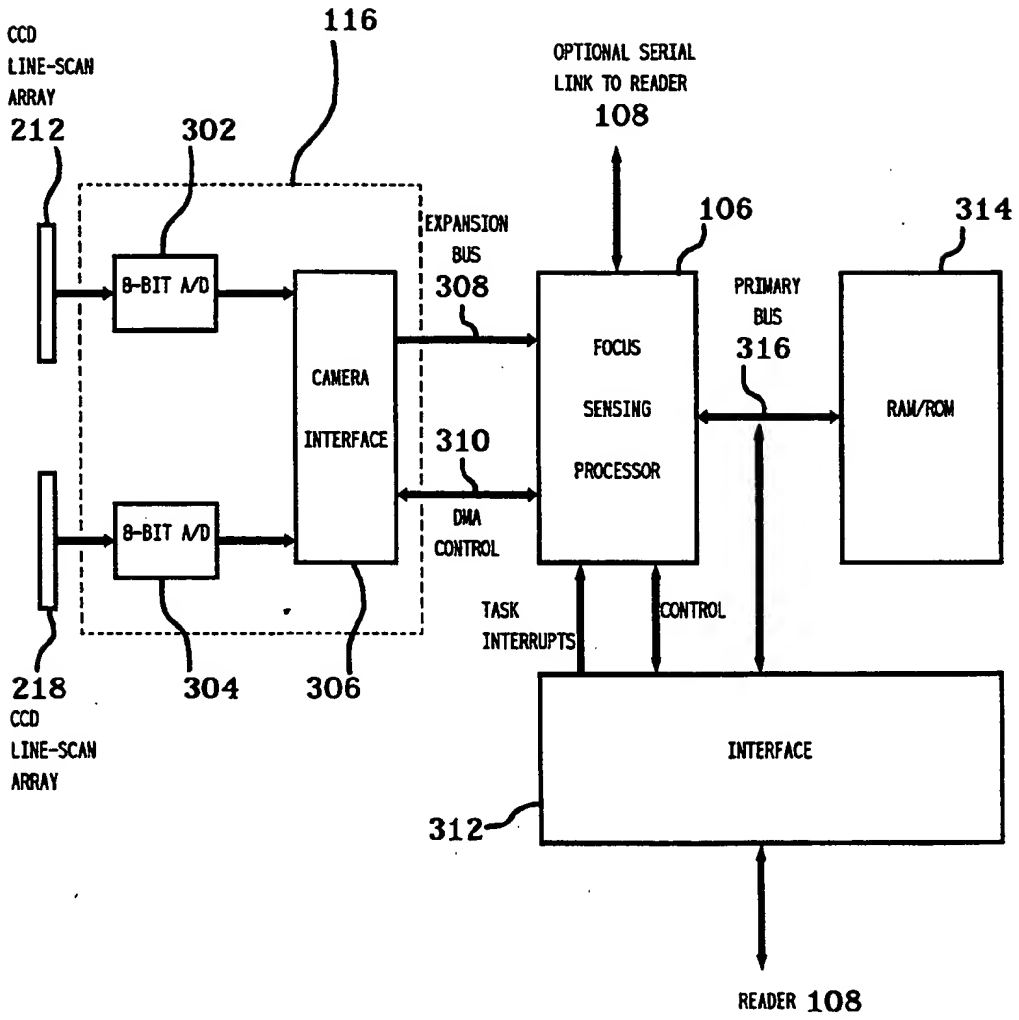

116
CCD
LINE-SCAN
ARRAY
212
302
OPTIONAL SERIAL
LINK TO READER
108
106
314
EXPANSION
BUS
308
8-BIT A/D
CAMERA
INTERFACE
FOCUS
SENSING
PROCESSOR
PRIMARY
BUS
316
RAM/ROM
310
8-BIT A/D
DMA
CONTROL
TASK
INTERRUPTS
CONTROL
218
304
306
CCD
LINE-SCAN
ARRAY
INTERFACE
312
READER 108

FIGURE 4.

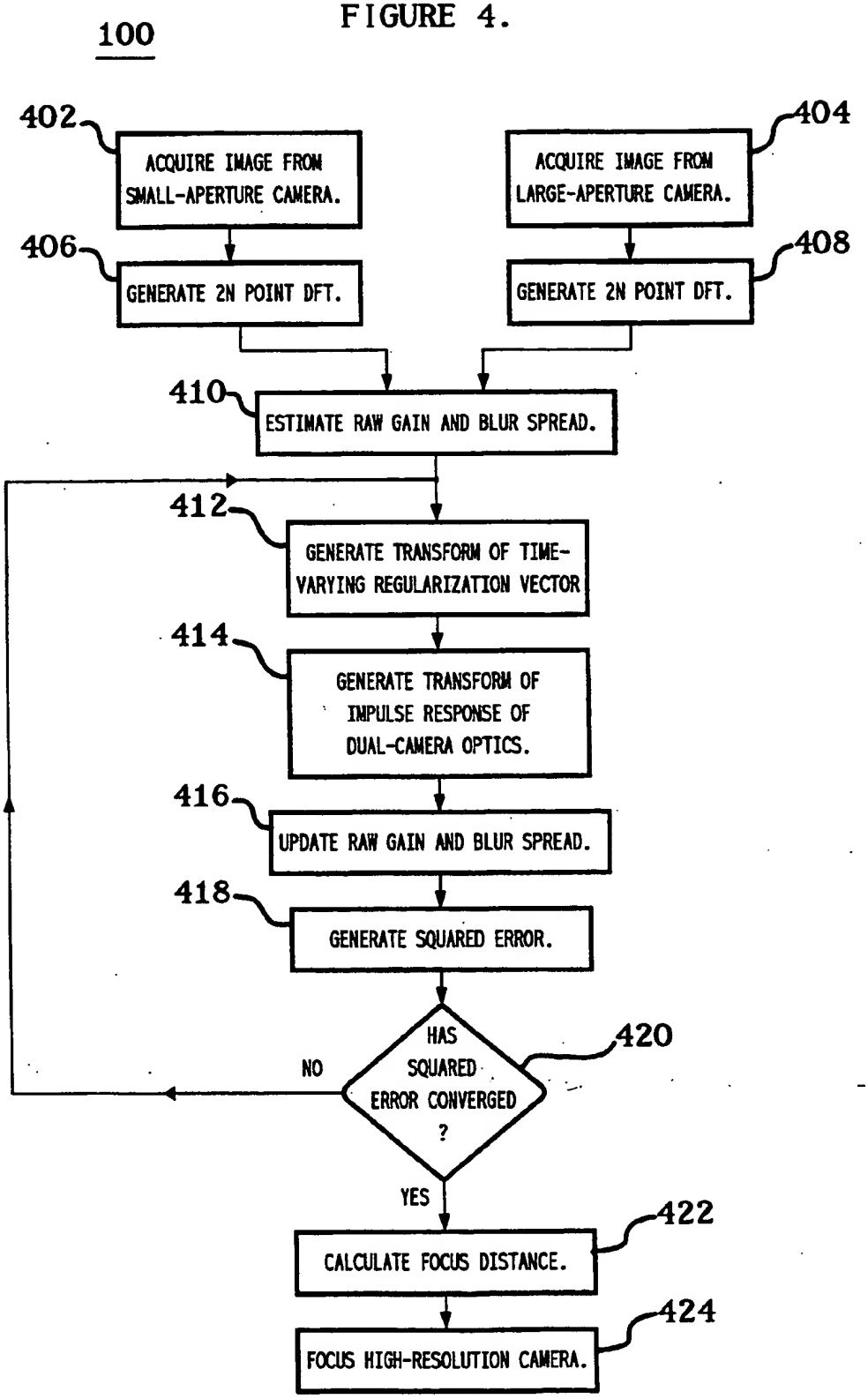

100
402
ACQUIRE IMAGE FROM SMALL-APERTURE CAMERA.
404
ACQUIRE IMAGE FROM LARGE-APERTURE CAMERA.
406
GENERATE 2N POINT DFT.
408
GENERATE 2N POINT DFT.
410
ESTIMATE RAW GAIN AND BLUR SPREAD.
412
GENERATE TRANSFORM OF TIME-VARYING REGULARIZATION VECTOR
414
GENERATE TRANSFORM OF IMPULSE RESPONSE OF DUAL-CAMERA OPTICS.
416
UPDATE RAW GAIN AND BLUR SPREAD.
418
GENERATE SQUARED ERROR.
420
HAS SQUARED ERROR CONVERGED ?
NO
YES
422
CALCULATE FOCUS DISTANCE.
424
FOCUS HIGH-RESOLUTION CAMERA.

FIGURE 5.

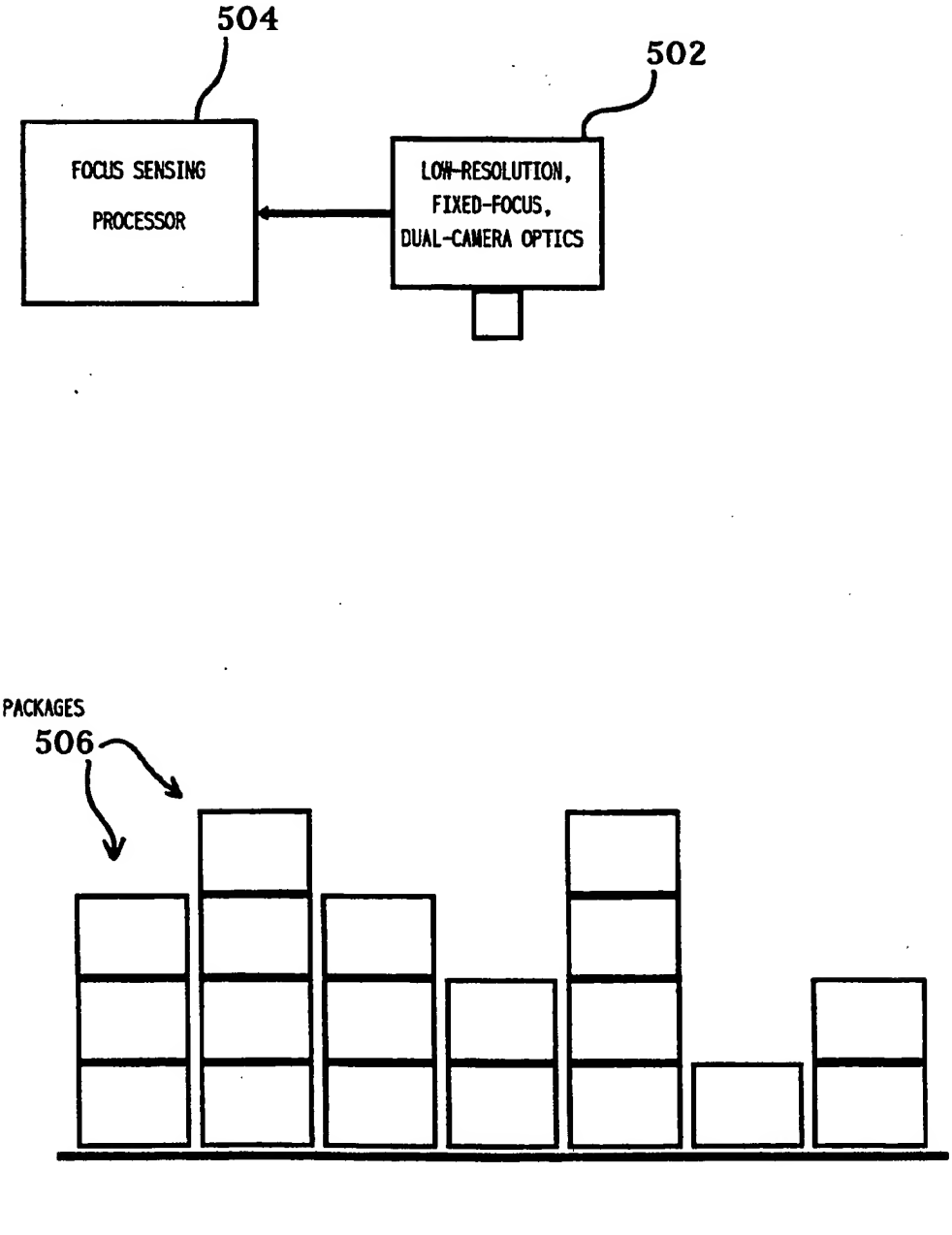

500
504
502
FOCUS SENSING
PROCESSOR
LOW-RESOLUTION,
FIXED-FOCUS,
DUAL-CAMERA OPTICS
PACKAGES
506

FIGURE 6.

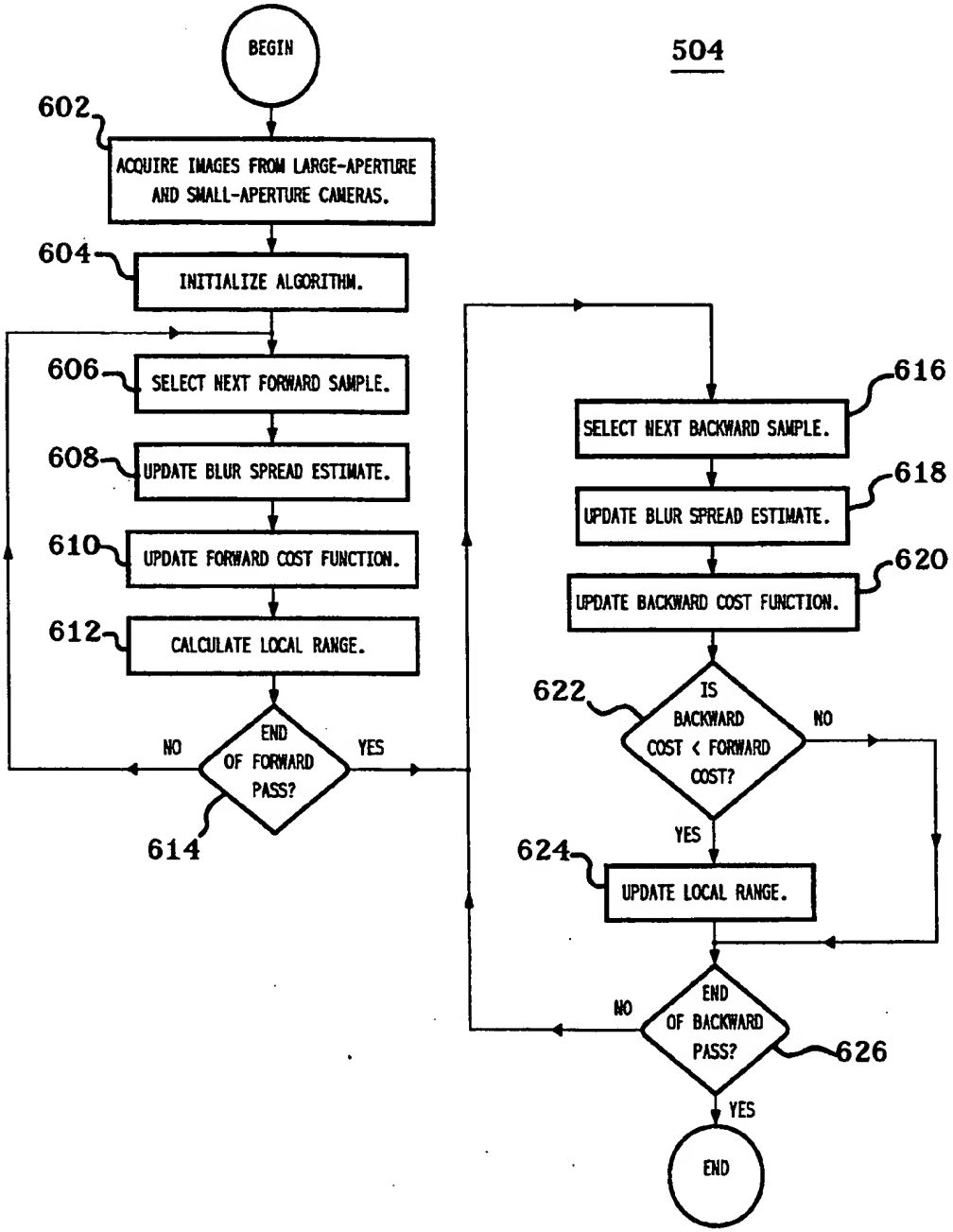
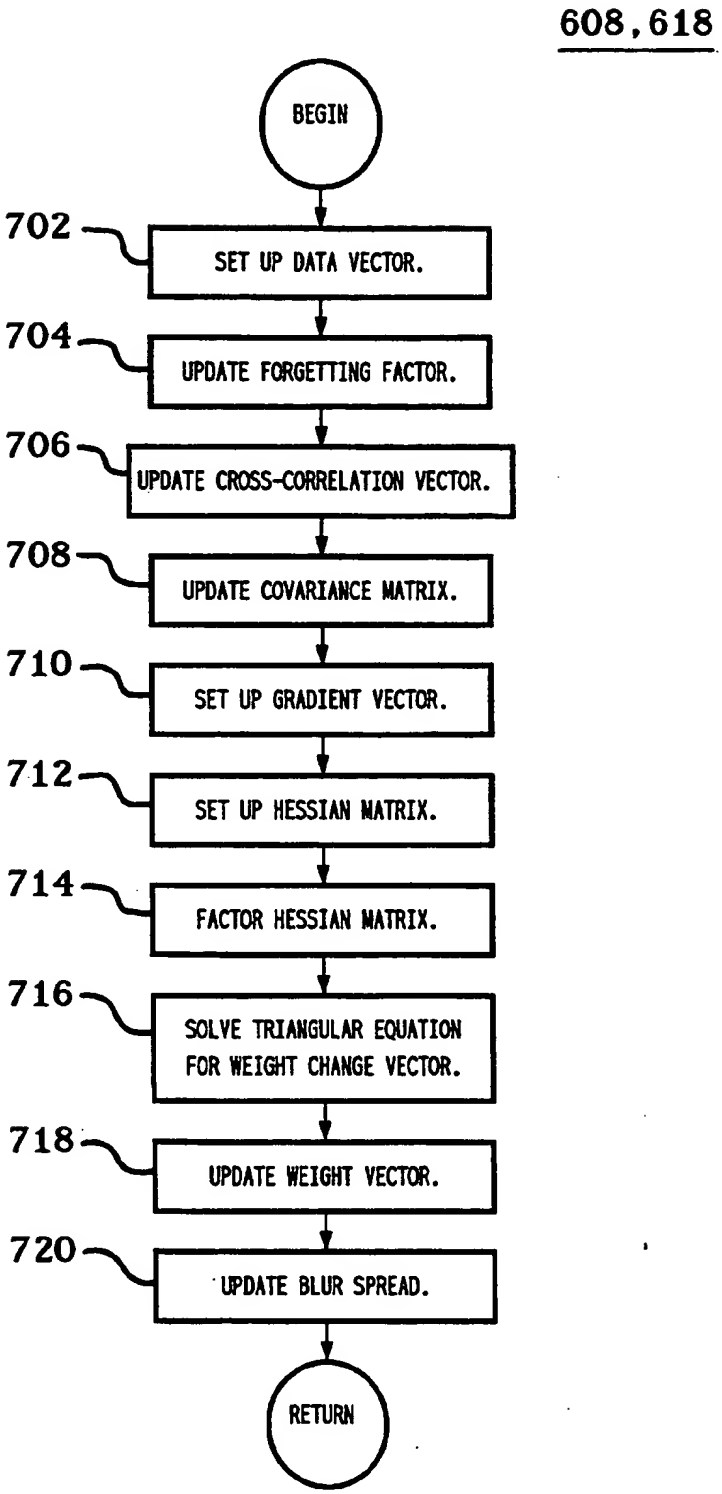

504
BEGIN
602
ACQUIRE IMAGES FROM LARGE-APERTURE AND SMALL-APERTURE CAMERAS.
604
INITIALIZE ALGORITHM.
606
SELECT NEXT FORWARD SAMPLE.
608
UPDATE BLUR SPREAD ESTIMATE.
610
UPDATE FORWARD COST FUNCTION.
612
CALCULATE LOCAL RANGE.
END OF FORWARD PASS?
NO
YES
614
616
SELECT NEXT BACKWARD SAMPLE.
618
UPDATE BLUR SPREAD ESTIMATE.
620
UPDATE BACKWARD COST FUNCTION.
622
IS BACKWARD COST < FORWARD COST?
NO
YES
624
UPDATE LOCAL RANGE.
END OF BACKWARD PASS?
NO
626
YES
END

FIGURE 7.



05/06/2004, EAST Version: 1.4.1

METHOD AND APPARATUS FOR PASSIVE AUTORANGING USING RELAXATION

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to autoranging, and, in particular, to passive methods and apparatuses for determining the range of one or more objects and/or for focussing a camera.

2. Description of the Related Art

In the field of package shipping, it is desirable to have a camera positioned overhead a conveyor system to read package labels as packages are propelled along the conveyor system. Since package heights may vary greatly, the field of view of the camera may also vary greatly. It is therefore desirable to use a high-resolution camera (e.g., with a 4096-pixel linear array charge coupled device (CCD) sensor) to generate images of the package labels. The camera system preferably provides autofocussing of the high-resolution camera to adjust for the varying package heights.

One known technique for focussing an overhead camera employs a light curtain consisting of a one-dimensional vertical array of light-emitting diodes (LED) and a matching one-dimensional vertical array of photo-transistors. The LED array is positioned on one side of the conveyor to transmit radiation across the conveyor path toward the photo-transistor array positioned on the other side of the conveyor. Package height is indicated by the lowest non-interrupted light beam as the package passes between the LED and photo-transistor arrays. This height estimate is then used to focus the high-resolution overhead camera.

This technique of autoranging can only measure the highest point of a stack of packages. Moreover, the resolution is limited by the density of LED/photo-transistor pairs in the matched arrays.

This technique of autoranging also employs active autofocussing, wherein radiation is generated with the specific purpose of focussing. Active autofocussing contrasts with passive autofocussing in which only ambient radiation is required to perform the focussing function.

Another known technique for determining package height employs scanned-laser triangulation. In this technique, a laser spot is scanned across the package surface by means of either a gavanometer stepped mirror or by a rotating mirror polygon. The range of the package is inversely proportional to the displacement of the reflected spot as imaged by either a line-scan CCD array or by a lateral-effect photodiode (i.e., a position sensing device).

This technique takes considerable time to scan mechanically the laser spot and limits the applicability of this technique to slow moving conveyor systems. In addition, there is the risk of injury to people from the laser radiation.

Yet another known technique for determining package height employs projected-pattern triangulation. In this technique, either a single light strip or a pattern of light strips are projected onto a package surface. Displacements of the projected light pattern imaged by a two-dimensional CCD array are inversely proportional to the range of the package.

Under this technique, the projected light pattern may be difficult to see in the presence of intense ambient light used for the high-resolution camera. Moreover, it takes considerable time to acquire a two-dimensional image.

It is also desirable, in the field of package shipping, to determine the heights of stacks of nested packages. Robots are preferably used to place and remove packages from nested stacks for storage and/or shipping. To function efficiently and automatically, the robots preferably have information regarding the height of each package stack.

Subbarao (U.S. Pat. No. 4,965,840) discloses the use of a pair of cameras with differing parameters and characteristics to image a scene for the purposes of either object range determination or autofocussing. The system of Subbarao estimates blur spread, which may then be used to determine object range and/or generate autofocus parameters. However, the system of Subbarao employs an algorithm that requires knowledge of the camera parameters for the pair of cameras, such as the aperture size, the focal length, and the distance between the second principal plane and the image detector plane.

It is accordingly an object of the present invention to overcome the disadvantages and drawbacks of the prior art and to provide an improved passive system for range determination and/or camera focussing.

It is a further object of the present invention to provide a system for passive autoranging without requiring any knowledge of camera parameters such as aperture size, focal length, or the distance between the second principal plane and the image detector plane.

It is a further object of the present invention to focus a high-resolution camera positioned overhead a conveyor system in order to generate images to read labels on packages on the conveyor system.

It is a further object of the present invention to determine the heights of a plurality of stacks of nested packages.

It is a further object of the present invention to stabilize the blur-spread estimates to random variations of the data (i.e., the perceived images). Stabilized blur-spread estimates imply more consistent and more accurate range and focus setting calculations.

Further objects and advantages of this invention will become apparent from the detailed description of a preferred embodiment which follows.

SUMMARY OF THE INVENTION

The present invention is a method and apparatus for determining at least one blur spread corresponding to at least one object. According to a preferred embodiment, a first image of at least one object is provided, where the first image is generated by a camera having a first camera parameter. A second image of the object is also provided, where the second image is generated by a camera having a second camera parameter different from the first camera parameter. A relaxation procedure is performed in accordance with the first and second images to generate at least one blur spread.

According to an alternative preferred embodiment, a first image of at least one object is provided with a first camera having a first focal length, a first aperture size, a first distance between a second principal plane and an image detector plane of the first camera, and a first camera parameter. A second image of the object is also generated, where the second image is generated with a camera having a second camera parameter different from the first camera parameter. At least one blur spread is generated in accordance with the first and

second images and independent of the first focal length, the first aperture size, and the first distance of the first camera.

An advantage of the present invention is that it provides autoranging passively, that is, using ambient radiation.

Another advantage of the present invention is that a preferred embodiment may be used to provide passive autofocussing of a camera.

Another advantage of the present invention is that an alternative preferred embodiment may be used to determine the profile of heights of nested packages in stacks.

Another advantage of the present invention is that preferred embodiments have no moving parts.

Another advantage of the present invention is that preferred embodiments provide precise autoranging over relatively large depths of view.

Another advantage of the present invention is that preferred embodiments provide autofocussing in a relatively short period of time and are therefore applicable to fast moving conveyor systems.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects, features, and advantages of the present invention will become more fully apparent from the following detailed description of the preferred embodiment, the appended claims, and the accompanying drawings in which:

FIG. 1 is a block diagram of a system for passive autofocussing according to a preferred embodiment of the present invention;

FIG. 2 is a schematic diagram of the optical system of the dual-camera optics of the system of FIG. 1;

FIG. 3 is a block diagram of the camera hardware of the dual-camera optics and the focus sensing processor of the system of FIG. 1;

FIG. 4 is a block flow diagram of the processing of the system of FIG. 1;

FIG. 5 is a block diagram of a system for determining the heights of a plurality of stacks of nested packages according to a preferred embodiment of the present invention;

FIG. 6 is a block flow diagram of the processing of the system of FIG. 5; and

FIG. 7 is a block flow diagram of the processing of the means of the system of FIG. 5 for updating the blur-spread estimate for the current sample.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

Preferred embodiments of the present invention are directed to systems for determining the range of at least one object from a blur-spread estimate, where the blur-spread estimate is generated via a procedure such as a relaxation procedure that receives as input two images of the object generated by cameras having different image parameters such as focal gradients. Depending upon the application, systems according to the present invention may employ a temporal relaxation procedure to determine a single blur-spread estimate or a spatial relaxation procedure to determine multiple blur-spread estimates. Each blur-spread estimate may be used to determine the range of an object in the two images. Thus, when a spatial relaxation procedure is employed, the multiple blur-spread estimates may be used to determine the ranges of multiple objects in the two images.

In one preferred embodiment, a system according to the present invention employs a temporal relaxation procedure to focus a high-resolution camera positioned overhead packages on a conveyor system. Such a system is described in further detail later in this specification in conjunction with FIGS. 1–4. In another preferred embodiment, a system according to the present invention employs a spatial relaxation procedure to determine the heights of a plurality of stacks of nested packages. Such a system is described in further detail later in this specification in conjunction with FIGS. 5–7.

Focussing an Overhead Cameras Using Temporal Relaxation

Referring to FIG. 1, there is shown a block diagram of system 100 for passive autofocussing according to a preferred embodiment of the present invention. System 100 includes conveyor belt 102, low-resolution, fixed-focus, dual-camera optics 104, focus sensing processor 106, label reader 108, and high-resolution, variable-focus camera 110. Dual-camera optics 104 has optical system 114 and camera hardware 116. Optical system 114 and camera hardware 116 are described in further detail later in this specification in conjunction with FIGS. 2 and 3, respectively.

Package 112 is propelled along belt 102 passing first under dual-camera optics 104 and then under high-resolution camera 110. As package 112 passes under dual-camera optics 104, dual-camera optics 104 generates two images, each image perceived by cameras having different focal gradients, of the top of package 112. Both images are transmitted to focus sensing processor 106, which performs a temporal relaxation procedure based on the two images to generate a blur-spread estimate. Focus sensing processor 106 uses the blur-spread estimate to calculate the focus distance for high-resolution camera 110, which transmitted to label reader 108. Label reader 108 uses the focus distance to focus camera 110 in time to generate a high-resolution image of the top of package 112 as package 112 passes under camera 110.

Camera 110 may be a conventional high-resolution, variable-focus camera and is preferably a 4096-pixel CCD line-scan array to enable perception of details on package labels. Label reader 108 may be any conventional computing device and is preferably a special purpose computer for decoding package labels. Conveyor belt 102 may be any conventional conveyor system.

Referring now to FIG. 2, there is shown a schematic diagram of optical system 114 of dual-camera optics 104 of FIG. 1. Optical system 114 includes objective lens 202, beamsplitter 204, small focal gradient camera 206, and large focal gradient camera 208. Small focal gradient camera 206 includes aspherical lens 210 and CCD line-scan array 212. Large focal gradient camera 208 includes neutral density filter 214, aspherical lens 216, and CCD line-scan array 218. Aperture 220 of small focal gradient camera 206 is smaller than aperture 222 of large focal gradient camera 208.

In a preferred embodiment, ambient light is reflected from the surface of a package and passes through objective lens 202 to beamsplitter 204. Beamsplitter 204 transmits some radiation to camera 206 and reflects some radiation to camera 208. Cameras 206 and 208 simultaneously generate images of the top of the package. Since cameras 206 and 208 have different aperture sizes, cameras 206 and 208 have different f-numbers and different focal gradients. Camera 206, having a relatively small aperture 220, has a relatively large f-number and a

relatively small focal gradient. On the other hand, camera **208**, having a relatively large aperture **222**, has a relatively small f-number and a relatively large focal gradient.

The specific characteristics of the optical components of optical system **114** of dual-camera optics **104** depend on the particular application and may be selected empirically. In general, the larger the ratio of camera **206** f-number to camera **208** f-number, the more accurate are the blur-spread estimates and hence the more accurate are the generated ranges. The specific component characteristics described below apply to a preferred embodiment of the present invention designed to provide a depth-of-view of approximately 24 inches and a field-of-view of approximately 18 inches.

Lens **202** may be a conventional biconvex objective lens and preferably has a focal length of 300 mm. Beamsplitter **204** may be a conventional plate beamsplitter and is preferably a 30/70 split beamsplitter. Lenses **210** and **216** may be conventional aspherical lenses and preferably have focal lengths of 8.5 mm. Filter **214** may be a conventional neutral density filter and is preferably selected empirically to prevent small f-number camera **208** from saturating when a package remains within the field of view. Arrays **212** and **218** may be conventional CCD line-scan arrays and are preferably 256-element CCD line scan arrays. In a preferred embodiment, camera **206** has an f-number of 12.5 and camera **208** has an f-number of 1.25. In alternative preferred embodiments, f-numbers for cameras **206** and **208** are selected to provide an f-number ratio of greater than 10.

Objective lens **202** determines the focal lengths of cameras **206** and **208**. Beamsplitter **204** allows cameras **206** and **208** to generate simultaneous images with cameras **206** and **208** oriented at right angles to one another. Filter **214** attenuates the light received by large-aperture camera **208** to ensure that the images generated by cameras **206** and **208** have similar intensity levels. Aspherical lenses **210** and **216** provide space for beamsplitter **204** and permit optimization of the optical characteristics of optical system **114** for the wavelengths of the ambient light. In a preferred embodiment, the ambient light is generated by a sodium arc lamp which illuminates packages for high-resolution imaging by camera **110** of FIG. **1**.

Referring now to FIG. **3**, there is shown a block diagram of camera hardware **116** of dual-camera optics **104** and focus sensing processor **106** of FIG. **1** according to a preferred embodiment of the present invention. CCD line-scan arrays **212** and **218** are the arrays of cameras **206** and **208**, respectively, as shown in FIG. **2**. Arrays **212** and **218** transmit analog pixel data to 8-bit A/D converters **302** and **304**, respectively. The digitized pixel data is then transmitted to camera interface **306** which stores the digital pixel data for transmission to focus sensing processor **106** via expansion bus **308**. Bus **310** provides direct memory access (DMA) control lines allowing direct access to RAM memory **314** from camera interface **306**. Camera interface **306** transfers image data directly to memory **314**, independent of focus sensing processor **106**.

Focus sensing processor **106** employs a relaxation procedure to process the two digital images generated by cameras **206** and **208** to calculate the focus distance for high-resolution camera **110**, which is transmitted to label reader **108** via interface **312**. The relaxation procedure implemented by focus sensing processor **106** is described in greater detail later in this specification in conjunction with FIG. **4**. Focus sensing processor **106** also stores data to and accesses data from RAM/ROM memory **314** via primary bus **316**.

Converters **302** and **304** may be conventional 8-bit A/D converters and are preferably flash-type converters. Interface **306** is preferably a custom-made interface that allows transfer of camera data to RAM memory **314**. Buses **308**, **310**, and **316** are preferably conventional bit-parallel digital buses. Focus sensing processor **106** is a digital signal processor preferably based on a Texas Instruments TMS30C30 Processor. Interface **312** is preferably a custom-made interface. Memory **314** is preferably a mixture of static RAM and EPROM.

Referring now to FIG. **4**, there is shown a block flow diagram of the processing implemented by system **100** of FIG. **1** for passive autofocussing of a high-resolution camera according to a preferred embodiment of the present invention. According to this processing, the two images generated by dual-camera optics **104** are processed by focus sensing processor **106** according to a temporal relaxation procedure to generate a blur-spread estimate. The relaxation procedure is an non-linear iterative procedure that is repeated until an acceptable blur-spread estimate is generated. The blur-spread estimate is then used to calculate the focus distance used by label reader **108** to focus high-resolution camera **110**.

In particular, step **402** of system **100** acquires the small-focal-gradient image from small-aperture camera **206** of FIG. **2**. Simultaneously, step **404** acquires the large-focal-gradient image from large-aperture camera **208**. Step **406** generates a 2N point discrete Fourier transform (DFT) of the small-focal-gradient image and step **408** generates a 2N point DFT of the large-focal-gradient image. The DFT is preferably calculated by a fast Fourier transform (FFT) algorithm, such as the algorithm described in *Digital Signal Processing* by Oppenheim and Schafer, Prentice-Hall, 1975.

Step **410** uses the two DFT's of the two images to estimate the raw gain κ and blur spread σ according to Equations (1) and (2) below:

$$\kappa = \exp\left(\frac{\left(\sum_j f^4\right)A(j) - \left(\sum_j f^2\right)B(j)}{2\left(N\sum_j f^4 - \left(\sum_j f^2\right)^2\right)}\right) \quad (1)$$

and

$$\sigma = \sqrt{2\frac{\left(\sum_j f^2\right)A(j) - NB(j)}{N\sum_j f^4 - \left(\sum_j f^2\right)^2}}, \quad (2)$$

where:

$$A(j) = \sum_j [\log P_f(j) - \log P_s(j)]$$

and

$$B(j) = \sum_j f^2[\log P_f(j) - \log P_s(j)],$$

where $P_f(j)$ is sample j of the power spectrum P_f of the large-focal-gradient image; $P_s(j)$ is sample j of the power spectrum P_s of the small-focal-gradient image;

and N is the number of pixels in each image. The power spectra P_l and P_s are generated according to Equations (3) and (4) as follows:

$$P_l = D_l^* D_l \tag{3}$$

and

$$P_s = D_s^* D_s \tag{4}$$

where D_l is the 2N point DFT of the large-focal-gradient image generated by step **408**; D_s is the 2N point DFT of the small-focal-gradient image generated by step **406**; D_l^* is the complex conjugate of D_l; and D_s^* is the complex conjugate of D_s.

Step **412** generates the transform $\overline{G}$ of the time-varying regularization vector according to Equation (5) as follows:

$$\overline{G} = \left[\kappa, \kappa \exp\left(\frac{-\sigma^2}{4}\right), \ldots, \kappa \exp\left(\frac{-(N-1)^2\sigma^2}{4}\right), \ldots, \kappa \exp\left(\frac{-\sigma^2}{4}\right), \kappa\right]^t \tag{5}$$

Step **414** generates an estimate of the transform $\overline{H}$ of the impulse response of dual-camera optics **104** of FIG. **1** according to Equation (6) as follows:

$$\overline{H} = \text{diagonal}\left[\frac{1}{x_j^* x_j + \mu}\right](X^* \overline{D}_1 + \mu\overline{G}), \tag{6}$$

where X^* is the complex conjugate of X; X is the diagonal matrix of the DFT of the small-focal-gradient image, such that $X = \text{diagonal}\,[X_j;\ k=0, 1, \ldots, 2N-1]$; μ is the fixed regularization parameter; x_j^* is the complex conjugate of x_j; and x_j is sample [j,j] along the diagonal of the DFT of the small-focal-gradient image. The fixed regularization parameter μ may be empirically determined and preferably has a value of 100. The value of regularization parameter μ is selected empirically to provide a good fit to the camera model and sufficient dynamic range of blur-spread estimates. The larger the value of μ, the smaller the dynamic range, but the better the fit to the camera model.

Step **416** updates the current estimates for the raw gain κ and the blur spread σ according to Equations (7) and (8) as follows:

$$\kappa = \exp\left(\frac{\left(\sum_j f^4\right)F(j) - \left(\sum_j f^2\right)G(j)}{2\left(N\sum_j f^4 - \left(\sum_j f^2\right)^2\right)}\right) \tag{7}$$

and

$$\sigma = \sqrt{2\frac{\left(\sum_j f^2\right)F(j) - NG(j)}{N\sum_j f^4 - \left(\sum_j f^2\right)^2}} \tag{8}$$

where:

-continued

$$F(j) = \sum_j \log[H(j)H^*(j)]$$

and

$$G(j) = \sum_j f^2 \log[H(j)H^*(j)]$$

Step **418** generates the current squared error $E_{squared}$ according to Equation (9) as follows:

$$E_{squared} = \sum_{j=0}^{N-1}\left(\log\left[(H(j)H^*(j)] - \kappa + \frac{\sigma^2 f^2}{2}\right)\right)^2, \tag{9}$$

where H(j) is the j^{th} sample of the transform $\overline{H}$ of the impulse response of dual-camera optics **104** and $H^*(j)$ is the complex conjugate of H(j).

Step **420** then determines whether the current blur-spread estimate σ is acceptable by testing for convergence of the squared error $E_{squared}$. In a preferred embodiment, step **420** determines whether the magnitude of the difference between the current squared error and the previous squared error (i.e., the squared error from the previous iteration cycle) is less than or equal to a specified threshold. If not, then the squared error has not yet sufficiently converged and processing returns to repeat the processing of step **412** through **420**. Processing continues to iterate until step **420** determines that the squared error has converged. At that time, processing proceeds to step **422**.

Step **422** calculates the focus distance d_i for high-resolution camera **110** according to Equation (10) below:

$$d_i = c_1\left(\frac{c_2 + \sigma}{c_3 + \sigma}\right), \tag{10}$$

where c_1, c_2, and c_3 are calibrated values for mapping from large-aperture camera **208** to high-resolution camera **110**.

The values for c_1, c_2, and c_3 are determined during a two-step calibration procedure. The first step is to acquire a N sets of pairs of focus distances d_i and blur-spread estimates σ_i by manually focussing high-resolution camera **110** on packages of different heights and determining the corresponding blur-spread estimates in images generated with dual-camera optics **104**. The second step is to solve a set of three linear equations that minimize the cost function E with respect to c_1, c_3, and K, where the cost function E is given by:

$$E = \sum_{i=1}^{N}(c_3 d_i - c_1\sigma_i - K + d_i\sigma_i)^2$$

After step **422** calculates the focus distance d_i, step **424** then focusses high-resolution camera **110** based on the calculated focus distance d_i. In a preferred embodiment of the present invention, focus sensing processor **106** implements steps **402** through **422** and label reader **108** implements step **424**.

Those skilled in the art will understand that dual-camera optics **104** and focus sensing processor **106** may be designed for a range-finding system that determines the distance between dual-camera optics **104** and an

imaged object. Such a system may or may not focus a camera.

Those skilled in the art will also understand that means other than dual-camera optics **104** may be used to generate the two images that are inputs to the relaxation procedure of the present invention. For example, two cameras having different parameters such as aperture size, focal length, and/or distance between the second principal plane and the image detector plane will have different focal gradients and may be used to generate the two images. Moreover, a single camera may be used to generate the two images if the focal gradient of the camera is changed from one image to the other.

Multiple Range-Finding Using Spatial Relaxation

Referring now to FIG. 5, there is shown a block diagram of system **500** for determining the heights of a plurality of stacks of nested packages according to a preferred embodiment of the present invention. System **500** includes low-resolution, fixed-focus, dual-camera optics **502** and focus sensing processor **504**.

Dual-camera optics **502** is positioned above a plurality of stacks of nested packages **506**. Dual-camera optics **502** has two cameras with different focal gradients and generates two images of the tops of the stacks of nested packages **50**e within the field of view of dual-camera optics **502**. Both images are transmitted to focus sensing processor **504**, which performs a spatial relaxation procedure based on the two images to generate a blur-spread estimate for each image sample (i.e., pixel). Each image sample corresponds to a different position in the field of view of dual-camera optics **502**. Focus sensing processor **504** calculates a range value from each blur-spread estimate, where each range value corresponds to the height of a stack of nested packages **506**.

In a preferred embodiment of system **500**, the hardware of dual-camera optics **502** and focus sensing processor **504** is identical to that of dual-camera optics **104** and focus sensing processor **106** of system **100** of FIG. **1**, respectively. The processing implemented by focus sensing processor **504**, however, differs from the processing of focus sensing processor **106**.

Referring now to FIG. 6, there is shown a block flow diagram of the processing of focus sensing processor **504** according to a preferred embodiment of the present invention. Focus sensing processor **504** uses the two images generated by dual-camera optics **502** of FIG. 5 as inputs to a spatial relaxation procedure. The spatial relaxation procedure includes two spatial passes through the image data: a forward pass in one direction and a backward pass in the opposite direction.

During the forward pass, focus sensing processor **504** sequentially selects samples from the large-focal-gradient image generated by the large-aperture camera of dual-camera optics **502** and corresponding samples from the small-focal-gradient image generated by the small-aperture camera of dual-camera optics **502**. Focus sensing processor **504** generates a forward blur-spread estimate for each sample pair. Each blur-spread estimate is based in part on the blur-spread estimates for the previously selected samples. From each blur-spread estimate, focus sensing processor **504** calculates a forward cost function value and a range value.

After the forward pass is complete, focus sensing processor **504** performs analogous processing in a backward pass through the image data, in which the image samples are selected in the opposite order from those in the forward pass. Focus sensing processor **504** generates a backward blur-spread estimate and a backward cost function value for each sample during the backward pass. If the backward cost function value for a particular sample is less than the forward cost function value for the same sample, then focus sensing processor **504** updates the range value for that sample using the backward blur-spread estimate. When the backward pass is complete, focus sensing processor **504** will have generated a set of range values, each of which corresponds to a different image sample and therefore to a different position within the field of view of dual-camera optics **502**. These range values can then be used to determine the various heights of the stacks of nested packages.

In particular, step **602** of focus sensing processor **504** acquires corresponding images from the large-aperture and small-aperture cameras of dual-camera optics **502**. Step **604** initializes the preferred spatial relaxation algorithm according to Equations (11)–(14) below:

$$R(0)=0 \tag{11}$$

$$\bar{\Theta}(0)=0 \tag{12}$$

$$\bar{w}(0)=[1\ 0\ \ldots\ 0]^t \tag{13}$$

$$\sigma(0)=1.0 \tag{14}$$

where R(0) is the initialized covariance matrix; $\bar{\Theta}(0)$ is the initialized cross-correlation vector; $\bar{w}(0)$ is the initialized weight vector; and $\sigma(0)$ is the initialized blur-spread estimate.

Step **606** selects the next forward sample n, where $n=1, \ldots, M$, where M is the number of samples in each image. Step **608** then updates the blur-spread estimate for the current sample.

Referring now to FIG. 7, there is shown a block flow diagram of the processing of step **608** of FIG. **6** for updating the blur-spread estimate for the current sample. Step **702** of step **608** sets up a data vector $\bar{u}(n)$ according to Equation (15) below:

$$\bar{u}(n)=[x(n),\ x(n-1)+x(n+1),\ \ldots,\ x(n-M+1)+x(n+M-1),\ 1]^t \tag{15}$$

where x(n) is the n^{th} sample from the small-focal-gradient image.

Step **704** updates a spatially variant forgetting factor $\lambda(n)$ according to Equation (16) below:

$$\lambda(n) = \lambda_{min} + \frac{(1-\lambda_{min})}{(\beta||\nabla x(n)||^2 + 1)} \tag{16}$$

where λ_{min} is the minimum forgetting factor value and β is a scale factor. The minimum forgetting factor value λ_{min} and the scale factor β may be empirically determined and preferably have values of 0.90 and 1.0, respectively.

Step **706** updates the cross-correlation vector $\bar{\Theta}(n)$ recursively according to Equation (17) below:

$$\bar{\Theta}(n)=\lambda(n)\bar{\Theta}(n-1)+d(n)\bar{u}(n) \tag{17}$$

where d(n) is n^{th} sample from the large-focal-gradient image.

Step **708** updates the covariance matrix R(n) recursively according to Equation (18) below:

$$R(n)=\lambda(n)R(n-1)+\bar{u}(n)\bar{u}(n) \tag{18}$$

where $\bar{u}^t(n)$ is the transpose of the data vector $\bar{u}(n)$.

Step **710** sets up a gradient vector $\nabla E(n)$, which is the derivative of a scalar cost function E(n) with respect to a weight vector $\bar{w}(n)$. Step **712** sets up a Hessian matrix H(n), which is the second derivative of the scalar cost function E(n) with respect to the weight vector $\bar{w}(n)$ and is given according to Equation (19) below:

$$H(n) = \frac{\partial^2 E(n)}{\partial \bar{w}(n) \partial \bar{w}^t(n)} \tag{19}$$

The weight vector $\bar{w}(n)$ and the scalar cost function E(n) are given below by Equations (21) and (23), respectively. The gradient vector $\nabla E(n)$ and the Hessian matrix H(n) are computed using the weight vector $\bar{w}(n-1)$ and blur-spread estimate $\sigma(n-1)$ from the previous sample n−1, but using the data vector $\bar{u}(n)$ from the current sample n.

Step **714** factors the Hessian matrix H(n) into the product of triangular matrices by the Cholesky reduction algorithm, as described in *Introduction to Matrix Computations*, by Stewart, Academic Press, 1973.

Means **716** determines a weight change vector $\Delta\bar{w}(n)$ by solving a triangulation equation given by Equation (20) below:

$$H(n)\Delta\bar{w}(n) = \nabla E(n) \tag{20}$$

Step **718** updates the weight vector $\bar{w}(n)$ according to Equation (21) below:

$$\bar{w}(n) = \bar{w}(n-1) - \alpha\Delta\bar{w}(n) \tag{21}$$

where α is the learning rate. The learning rate α may be empirically determined and preferably has a value of 1.0.

Step **720** updates the blur-spread estimate $\sigma(n)$ for the current sample n according to Equation (22) below:

$$\sigma(n) = \sqrt{\frac{\left(\sum_k w_k^2\right)\left(\sum_k k^4 w_k^2\right) - \left(\sum_k k^2 w_k^2\right)^2}{\left(\sum_k k^2 w_k^2\right)\left(\sum_k w_k^2 \log(w_k)\right) - \left(\sum_k w_k^2\right)\left(\sum_k k^2 w_k^2 \log(w_k)\right)}} \tag{22}$$

where w_k is the k^{th} element of the weight vector $\bar{w}(n)$.

Referring again to FIG. 6, after step **608** updates the blur-spread estimate $\sigma(n)$, step **610** updates the forward cost function E(n) according to Equation (23) below:

$$E(n) = \sum_{i=1}^{n} [\lambda(i)]^{n-i}[d(i) - \bar{u}^t(i)\bar{w}(n)]^2 + \sum_{k=1}^{4} \mu_k c_k(\bar{w}(n)) \tag{23}$$

where $\bar{u}^t(i)$ is the transpose of the data vector $\bar{u}(i)$; μ_k for k=1,2,3,4 are four regularization parameters; and $c_k(w(n))$ for k=1,2,3,4 are four constraint functions. The four regularization parameters may be empirically determined and preferably have values (μ_1=100.0); (μ_2=0.01); (μ_3=1.0); and (μ_4=1.0). As with the temporal relaxation method, the values of the four regularization parameters μ_k for the spatial relaxation method are selected to provide accurate blur/range estimates and sufficient dynamic range.

The four constraint functions $c_k(w(n))$ are given by Equations (24)–(27) below:

$$c_1(\bar{w}(n)) = \sum_{k=1}^{M-1}\left[w_k - w_0 \exp\left(-\frac{k^2}{\sigma^2(n-1)}\right)\right]^2 \tag{24}$$

$$c_2(\bar{w}(n)) = \left(\frac{1}{w_0^2}\right)\sum_{k=1}^{M-1} w_k^2 \tag{25}$$

$$c_3(\bar{w}(n)) = \left|\left| \frac{d}{dn}\bar{w}(n) \right|\right|^2 \tag{26}$$

$$c_4(\bar{w}(n)) = \left|\left| \frac{d^2}{dn^2}\bar{w}(n) \right|\right|^2 \tag{27}$$

where w_0 is the 0^{th} element of the weight vector $\bar{w}(n)$ and $\sigma^2(n-1)$ is the square of the blur-spread estimate from the previous sample (n−1). The first and second derivatives in Equations (26) and (27) may be approximated according to Equations (28) and (29) below:

$$\frac{d}{dn}\bar{w}(n) \approx \bar{w}(n) - \bar{w}(n-1) \tag{28}$$

$$\frac{d^2}{dn^2}\bar{w}(n) \approx \bar{w}(n) - 2\bar{w}(n-1) + \bar{w}(n-2) \tag{29}$$

where $\bar{w}(n)$ is the local average of past weight vectors and is generated according to Equation (30) below:

$$\bar{w}(n) = \frac{1}{\rho}\sum_{j=n-\rho+1}^{n} \bar{w}(j) \tag{30}$$

where ρ is an integer that specifies the number of previous samples used to generate the local average $\bar{w}(n)$. ρ may be empirically determined and preferably has a value of 3.0.

After step **610** updates the forward cost function E(n), step **612** calculates the local range z(n) for the current sample n according to Equation (31) below:

$$z(n) = z_m \frac{A + \sigma(n)}{B + \sigma(n)} \tag{31}$$

where z_m, A, and B are calibration parameters.

The method of determining values for the calibration parameters z_m, A, and B for the spatial relaxation method is analogous to the two-step calibration method for the temporal relaxation method described earlier in this specification. The first step is to acquire a N sets of pairs of focus distances z_i and blur-spread estimates σ_i by manually focussing high-resolution camera **110** on a target with a known profile and determining the corresponding blur-spread estimates across an image generated with dual-camera optics **104**. The second step is to solve a set of three linear equations that minimize the cost function E with respect to B, z_m, and C, where the cost function E is given by:

$$E = \sum_{i=1}^{N}(Bz_i - z_m\sigma_i - C + z_i\sigma_i)^2$$

where:

$$A = C/Z_m.$$

Step 614 determines whether the forward pass through the image data is complete (i.e., whether every sample has been selected for processing). If not, then processing returns to step 606 to select the next forward sample for processing by step 608, 610, and 612. Otherwise, the forward pass is complete and processing continues to step 616 to select the first sample for the backward pass through the image data. In a preferred embodiment, step 616 begins the backward pass by reselecting the last sample from the forward pass as the first sample for the backward pass. In addition, the relaxation algorithm is preferably not reinitialized at the beginning of the backward pass.

Step 618 and 620 update the blur-spread estimate $\sigma(n)$ and cost function E(n), respectively, for the current sample n during the backward pass. In a preferred embodiment, the processing of step 618 and 620 is analogous to that performed by step 608 and 610, respectively, as already described above. As in the forward pass, during the backward pass, in computing the value of the cost function E(n), the term due to the data (i.e., the first summation in Equation (23) above) is averaged, while the term due to the constraints (i.e., the second summation in Equation (23) above) is not averaged.

Step 622 compares the backward cost function value with the corresponding forward cost function value for the current sample. If the backward cost function value is less than the forward cost function value, then step 624 updates the local range value z(n) using the blur-spread estimate $\sigma(n)$ from the backward pass. In a preferred embodiment, step 624 employs processing analogous to that of step 612.

Step 626 then determines whether the backward pass through the image data is complete. If not, then processing returns to step 616 to select the next sample in the backward pass. Otherwise, processing of focus sensing processor 504 is complete. The resulting range values z(n) correspond to the heights of the stacks of nested packages in the field of view of dual-camera optics 502.

Those skilled in the art will understand that systems within the scope of the present invention may be used to determine the distances between dual-camera optics 502 and one or more objects other than stacks of nested packages.

It will also be understood by those skilled in the art that systems falling within the scope of the present invention may employ relaxation methods other than the specific temporal and spatial relaxation methods described in this specification. For example, the camera's power spectrum may be estimated by regularization with a cylindrical sinc function. Such a system uses the same temporal relaxation algorithm as described earlier in this specification in conjunction with FIG. 4, except that a cost function based on a cylindrical sinc function in frequency is used instead of the gaussian-based cost function $E_{squared}$ of Equation (9) above. Such a system may be useful for optical testing (i.e., determining just how well focussed a lens is or how well the details of a scene may be imaged).

In another alternative preferred embodiment, a robot may used the spatial relaxation method to determine depth profiles for stacking packages or other operations.

It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the principle and scope of the invention as expressed in the following claims.

What is claimed is:

1. A method for determining a differential blur spread corresponding to an object, comprising the steps of:
   (a) providing a first image of said object, said first image being generated by a camera having a first camera parameter;
   (b) providing a second image of said object, said second image being generated by a camera having a second camera parameter different from said first camera parameter; and
   (c) performing a relaxation procedure in accordance with said first and second images to generate said differential blur spread.

2. The method of claim 1, further comprising the step of:
   (d) determining a range of said object in accordance with said differential blur spread.

3. The method of claim 2, further comprising the step of:
   (e) focussing a camera in accordance with said range.

4. The method of claim 3, wherein said object is a package on a conveyor system and said focussed camera is a high-resolution camera positioned overhead said conveyor system to generate images used to read a label on said package.

5. The method of claim 1, wherein said first camera parameter is a first focal gradient and said second camera parameter is a second focal gradient.

6. The method of claim 1, wherein:
   step (a) comprises the step of generating said first image with a first camera having a first aperture size; and
   step (b) comprises the step of generating said second image with a second camera having a second aperture size, said second aperture size being different from said first aperture size.

7. The method of claim 1, wherein:
   step (a) comprises the step of generating said first image with a first camera having a first focal length; and
   step (b) comprises the step of generating said second image with a second camera having a second focal length, said second focal length being different from said first focal length.

8. The method of claim 1, wherein:
   step (a) comprises the step of generating said first image with a first camera having a first distance between a second principal plane and an image detector plane of said first camera; and
   step (b) comprises the step of generating said second image with a second camera having a second distance between a second principal plane and an image detector plane of said second camera, said second distance being different from said first distance.

9. The method of claim 1, wherein step (c) comprises the step of performing a temporal relaxation procedure in accordance with said first and second images to generate said differential blur spread.

10. The method of claim 1, wherein step (c) comprises the steps of:
   (1) generating a 2N point discrete Fourier transform of said first image;
   (2) generating a 2N point discrete Fourier transform of said second image;

(3) generating a raw gain and said differential blur spread in accordance with said 2N point discrete Fourier transforms of said first and second images;

(4) generating a transform of a time-varying regularization vector in accordance with said raw gain and said differential blur spread;

(5) generating a transform of an impulse response in accordance with said time-varying regularization vector and said 2N point discrete Fourier transforms of said first and second images;

(6) updating said raw gain and said differential blur spread in accordance with said impulse response;

(7) generating a squared error in accordance with said impulse response, said updated raw gain, and said updated differential blur spread;

(8) testing said squared error for convergence; and

(9) repeating steps (c)(4) through (c)(7) in accordance with said testing of step (c)(8).

11. The method of claim **1**, wherein step (c) comprises the step of performing a spatial relaxation procedure in accordance with said first and second images to generate said differential blur spread.

12. The method of claim **11**, wherein:

step (c) comprises the step of performing said spatial relaxation procedure in accordance with a forward pass through said first and second images to generate a plurality of forward differential blur spreads and a plurality of forward cost function values; and further comprising the steps of:

(d) determining a plurality of ranges corresponding to a plurality of objects in accordance with said plurality of forward differential blur spreads;

(e) performing said spatial relaxation procedure in accordance with a backward pass through said first and second images to generate a plurality of backward differential blur spreads and a plurality of backward cost function values;

(f) comparing said plurality of backward cost function values with said plurality of forward cost function values; and

(g) updating said plurality of ranges in accordance with said comparison of step (f).

13. The method of claim **1**, wherein step (c) comprises the steps of:

(1) selecting a first first-image sample from said first image and a corresponding first second-image sample from said second image;

(2) generating a first differential blur spread in accordance with said first first-image and first second-image samples;

(3) selecting a second first-image sample from said first image and a corresponding second second-image sample from said second image; and

(4) generating a second differential blur spread in accordance with said second first-image and second second-image samples.

14. The method of claim **13**, further comprising the steps of:

(d) determining a first range value corresponding to said first first-image and second-image samples in accordance with said first differential blur spread; and

(e) determining a second range value corresponding to said second first-image and second-image samples in accordance with said second differential blur spread.

15. The method of claim **14**, wherein said first range value corresponds to the height of a first stack of nested packages and said second range value corresponds to the height of a second stack of nested packages.

16. The method of claim **1**, wherein:

step (a) comprises the step of providing said first image with a first camera having a focal length, an aperture size, and a distance between a second principal plane and an image detector plane of said first camera, and

step (c) comprises the step of performing said relaxation procedure independent of said focal length, said aperture size, and said distance of said first camera.

17. An apparatus for determining a differential blur spread corresponding to object, comprising:

(a) a camera, having a first camera parameter, for providing a first image of said object;

(b) camera means, having a second camera parameter, for providing a second image of said object, said second camera parameter being different from said first camera parameter; and

(c) means for performing a relaxation procedure in accordance with said first and second images to generate said differential blur spread.

18. The apparatus of claim **17**, further comprising:

(d) means for determining a range of said object in accordance with said differential blur spread.

19. The apparatus of claim **18**, further comprising:

(e) means for focussing a camera in accordance with said range.

20. The apparatus of claim **19**, wherein said object is a package on a conveyor system and said camera is a high-resolution camera positioned overhead said conveyor system to generate images used to read a label on said package.

21. The apparatus of claim **17**, wherein said first camera parameter is a first focal gradient and said second camera parameter is a second focal gradient.

22. The apparatus of claim **17**, wherein:

camera (a) comprises a first camera having a first aperture size; and

camera means (b) comprises a second camera having a second aperture size, said second aperture size being different from said first aperture size.

23. The apparatus of claim **17**, wherein:

camera (a) comprises a first camera having a first focal length; and

camera means (b) comprises a second camera having a second focal length, said second focal length being different from said first focal length.

24. The apparatus of claim **17**, wherein:

camera (a) comprises a first camera having a first distance between a second principal plane and an image detector plane of said first camera; and

camera means (b) comprises a second camera having a second distance between a second principal plane and an image detector plane of said second camera, said second distance being different from said first distance.

25. The apparatus of claim **17**, wherein means (c) comprises means for performing a temporal relaxation procedure in accordance with said first and second images to generate said differential blur spread.

26. The apparatus of claim **17**, wherein means (c) comprises:

(1) means for generating a 2N point discrete Fourier transform of said first image and for generating a 2N point discrete Fourier transform of said second image;

(2) means for generating a raw gain and said differential blur spread in accordance with said 2N point discrete Fourier transforms of said first and second images;

(3) means for generating a transform of a time-varying regularization vector in accordance with said raw gain and said differential blur spread;

(4) means for generating a transform of an impulse response in accordance with said time-varying regularization vector and said 2N point discrete Fourier transforms of said first and second images;

(5) means for updating said raw gain and said differential blur spread in accordance with said impulse response;

(6) means for generating a squared error in accordance with said impulse response, said updated raw gain, and said updated differential blur spread; and

(7) means for testing said squared error for convergence.

27. The apparatus of claim 17, wherein means (c) comprises means for performing a spatial relaxation procedure in accordance with said first and second images to generate said differential blur spread.

28. The apparatus of claim 27, wherein:

means (c) comprises means for performing said spatial relaxation procedure in accordance with a forward pass through said first and second images to generate a plurality of forward differential blur spreads and a plurality of forward cost function values; and further comprising:

(d) means for determining a plurality of ranges corresponding to a plurality of objects in accordance with said plurality of forward differential blur spreads;

(e) means for performing said spatial relaxation procedure in accordance with a backward pass through said first and second images to generate a plurality of backward differential blur spreads and a plurality of backward cost function values;

(f) means for comparing said plurality of backward cost function values with said plurality of forward cost function values; and

(g) means for updating said plurality of ranges in accordance with said comparison of means (f).

29. The apparatus of claim 17, wherein means (c) comprises:

(1) means for:

(a) selecting a first first-image sample from said first image and a corresponding first second-image sample from said second image, and

(b) selecting a second first-image sample from said first image and a corresponding second second-image sample from said second image; and

(2) means for:

(a) generating a first differential blur spread in accordance with said first first-image and first second-image samples, and

(b) generating a second differential blur spread in accordance with said second first-image and second second-image samples,

30. The apparatus of claim 29, further comprising:

(d) means for:

(1) determining a first range value corresponding to said first first-image and second-image samples in accordance with said first differential blur spread; and

(2) determining a second range value corresponding to said second first-image and second-image samples in accordance with said second differential blur spread,

31. The apparatus of claim 30, wherein said first range value corresponds to the height of a first stack of nested packages and said second range value corresponds to the height of a second stack of nested packages.

32. The apparatus of claim 17, wherein:

camera (a) comprises a first camera having a focal length, an aperture size, and a distance between a second principal plane and an image detector plane of said first camera, and

means (c) comprises means for performing said relaxation procedure independent of said focal length, said aperture size, and said distance of said first camera.

33. A method for determining a differential blur spread corresponding to an object, comprising the steps of:

(a) providing a first image of said object with a first camera having a first focal length, a first aperture size, a first distance between a second principal plane and an image detector plane of said first camera, and a first camera parameter;

(b) generating a second image of said object, said second image being generated with a camera having a second camera parameter different from said first camera parameter; and

(c) generating said differential blur spread in accordance with said first and second images and independent of said first focal length, said first aperture size, and said first distance of said first camera.

34. The method of claim 33, further comprising the step of:

(d) determining a range of said object in accordance with said differential blur spread.

35. The method of claim 34, further comprising the step of:

(e) focussing a camera in accordance with said range.

36. The method of claim 35, wherein said object is a package on a conveyor system and said focussed camera is a high-resolution camera positioned overhead said conveyor system to generate images used to read a label on said package.

37. The method of claim 33, wherein said first camera parameter is a first focal gradient and said second camera parameter is a second focal gradient.

38. The method of claim 33, wherein step (b) comprises the step of generating said second image with a second camera having a second aperture size, said second aperture size being different from said first aperture size.

39. The method of claim 33, wherein step (b) comprises the step of generating said second image with a second camera having a second focal length, said second focal length being different from said first focal length.

40. The method of claim 33, wherein step (b) comprises the step of generating said second image with a second camera having a second distance between a second principal plane and an image detector plane of said second camera, said second distance being different from said first distance.

41. The method of claim 33, wherein step (c) comprises the step of performing a temporal relaxation procedure in accordance with said first and second images to generate said differential blur spread.

42. The method of claim 33, wherein step (c) comprises the steps of:

(1) generating a 2N point discrete Fourier transform of said first image;

(2) generating a 2N point discrete Fourier transform of said second image;

(3) generating a raw gain and said differential blur spread in accordance with said 2N point discrete Fourier transforms of said first and second images;

(4) generating a transform of a time-varying regularization vector in accordance with said raw gain and said differential blur spread;

(5) generating a transform of an impulse response in accordance with said time-varying regularization vector and said 2N point discrete Fourier transforms of said first and second images;

(6) updating said raw gain and said differential blur spread in accordance with said impulse response;

(7) generating a squared error in accordance with said impulse response, said updated raw gain, and said updated differential blur spread;

(8) testing said squared error for convergence; and

(9) repeating steps (c)(4) through (c)(7) in accordance with said testing of step (c)(8).

43. The method of claim **33**, wherein step (c) comprises the step of performing a spatial relaxation procedure in accordance with said first and second images to generate said differential blur spread.

44. The method of claim **43**, wherein:

step (c) comprises the step of performing said spatial relaxation procedure in accordance with a forward pass through said first and second images to generate a plurality of forward differential blur spreads and a plurality of forward cost function values; and further comprising the steps of:

(d) determining a plurality of ranges corresponding to a plurality of objects in accordance with said plurality of forward differential blur spreads;

(e) performing said spatial relaxation procedure in accordance with a backward pass through said first and second images to generate a plurality of backward differential blur spreads and a plurality of backward cost function values;

(f) comparing said plurality of backward cost function values with said plurality of forward cost function values; and

(g) updating said plurality of ranges in accordance with said comparison of step (f).

45. The method of claim **33**, wherein step (c) comprises the steps of:

(1) selecting a first first-image sample from said first image and a corresponding first second-image sample from said second image;

(2) generating a first differential blur spread in accordance with said first first-image and first second-image samples;

(3) selecting a second first-image sample from said first image and a corresponding second second-image sample from said second image; and

(4) generating a second differential blur spread in accordance with said second first-image and second second-image samples.

46. The method of claim **45**, further comprising the steps of:

(d) determining a first range value corresponding to said first first-image and second-image samples in accordance with said first differential blur spread; and

(e) determining a second range value corresponding to said second first-image and second-image samples in accordance with said second differential blur spread.

47. The method of claim **46**, wherein said first range value corresponds to the height of a first stack of nested packages and said second range value corresponds to the height of a second stack of nested packages.

48. An apparatus for determining a differential blur spread corresponding to an object, comprising:

(a) a first camera for providing a first image of said object, said first camera having a first focal length, a first aperture size, a first distance between a second principal plane and an image detector plane of said first camera, and a first camera parameter;

(b) means, having a second camera parameter, for generating a second image of said object, said second camera parameter being different from said first camera parameter; and

(c) means for generating said differential blur spread in accordance with said first and second images and independent of said first focal length, said first aperture size, and said first distance of said first camera.

49. The apparatus of claim **48**, further comprising:

(d) means for determining a range of said object in accordance with said differential blur spread.

50. The apparatus of claim **49**, further comprising:

(e) means for focussing a camera in accordance with said range.

51. The apparatus of claim **50**, wherein said object is a package on a conveyor system and said camera is a high-resolution camera positioned overhead said conveyor system to generate images used to read a label on said package.

52. The apparatus of claim **48**, wherein said first camera parameter is a first focal gradient and said second camera parameter is a second focal gradient.

53. The apparatus of claim **48**, wherein means (b) comprises a second camera having a second aperture size, said second aperture size being different from said first aperture size.

54. The apparatus of claim **48**, wherein means (b) comprises a second camera having a second focal length, said second focal length being different from said first focal length.

55. The apparatus of claim **48**, wherein means (b) comprises a second camera having a second distance between a second principal plane and an image detector plane of said second camera, said second distance being different from said first distance.

56. The apparatus of claim **48**, wherein means (c) comprises means for performing a temporal relaxation procedure in accordance with said first and second images to generate said differential blur spread.

57. The apparatus of claim **48**, wherein means (c) comprises:

(1) means for generating a 2N point discrete Fourier transform of said first image and for generating a 2N point discrete Fourier transform of said second image;

(2) means for generating a raw gain and said differential blur spread in accordance with said 2N point discrete Fourier transforms of said first and second images;

(3) means for generating a transform of a time-varying regularization vector in accordance with said raw gain and said differential blur spread;

(4) means for generating a transform of an impulse response in accordance with said time-varying

regularization vector and said 2N point discrete Fourier transforms of said first and second images;

(5) means for updating said raw gain and said differential blur spread in accordance with said impulse response;

(6) means for generating a squared error in accordance with said impulse response, said updated raw gain, and said updated differential blur spread; and

(7) means for testing said squared error for convergence.

58. The apparatus of claim 48, wherein means (c) comprises means for performing a spatial relaxation procedure in accordance with said first and second images to generate said differential blur spread.

59. The apparatus of claim 58, wherein:

means (c) comprises means for performing said spatial relaxation procedure in accordance with a forward pass through said first and second images to generate a plurality of forward differential blur spreads and a plurality of forward cost function values; and further comprising:

(d) means for determining a plurality of ranges corresponding to a plurality of objects in accordance with said plurality of forward differential blur spreads;

(e) means for performing said spatial relaxation procedure in accordance with a backward pass through said first and second images to generate a plurality of backward differential blur spreads and a plurality of backward cost function values;

(f) means for comparing said plurality of backward cost function values with said plurality of forward cost function values; and

(g) mean for updating said plurality of ranges in accordance with said comparison of means (f).

60. The apparatus of claim 48, wherein means (c) comprises:

(1) means for:

(a) selecting a first first-image sample from said first image and a corresponding first second-image sample from said second image, and

(b) selecting a second first-image sample from said first image and a corresponding second second-image sample from said second image; and

(2) means for:

(a) generating a first differential blur spread in accordance with said first first-image and first second-image samples, and

(b) generating a second differential blur spread in accordance with said second first-image and second second-image samples.

61. The apparatus of claim 60, further comprising:

(d) means for:

(1) determining a first range value corresponding to said first first-image and second-image samples in accordance with said first differential blur spread; and

(2) determining a second range value corresponding to said second first-image and second-image samples in accordance with said second differential blur spread.

62. The apparatus of claim 61, wherein said first range value corresponds to the height of a first stack of nested packages and said second range value corresponds to the height of a second stack of nested packages.

63. The method of claim 1, wherein step (c) comprises the steps of:

(1) generating an initial differential blur spread in accordance with said first and second images; and

(2) performing a recursive relaxation procedure in accordance with said first and second images and said initial differential blur spread to generate an improved differential blur spread.

64. The method of claim 1, wherein step (c) comprises the steps of:

(1) generating a 2N point discrete Fourier transform of said first image;

(2) generating a 2N point discrete Fourier transform of said second image;

(3) generating an initial gain and an initial differential blur spread in accordance with said 2N point discrete Fourier transforms of said first and second images;

(4) generating the discrete Fourier transform of a time-varying regularization vector in accordance with said initial gain and said initial differential blur spread;

(5) generating the discrete Fourier transform of the differential impulse response between said camera of step (a) and said camera of step (b) in accordance with said discrete Fourier transformed time-varying regularization vector;

(6) updating said initial gain and said initial differential blur spread in accordance with said discrete Fourier transformed differential impulse response;

(7) generating a squared error in accordance with said discrete Fourier transformed differential impulse response, said updated gain, and said updated differential blur spread;

(8) testing for the convergence of said squared error; and

(9) repeating steps (c)(4) through (c)(7), in accordance with said testing of step (c)(8), using said updated gain and said updated differential blur spread.

65. The method of claim 64, wherein step (c)(4) employs a gaussian blur model.

66. The method of claim 64, wherein step (c)(4) employs a cylindrical sinc blur model.

67. The method of claim 1, where step (c) comprises the steps of:

(1) setting an initial differential blur spread equal to 1.0;

(2) performing a forward pass through said first and second images to generate a plurality of forward differential blur spreads and a plurality of forward cost function values using local recursive parameter adaption in the spatial domain;

(3) performing a backward pass through said first and second images, starting where the forward pass ended, to generate a plurality of backward differential blur spreads and a plurality of backward cost function values using local recursive parameter adaption in the spatial domain; and

(4) selecting a plurality of local differential blur spreads corresponding to a plurality of image pixel locations, whereby each local differential blur spread is selected from a corresponding local forward differential blur spread and a corresponding local backward differential blur spread in accordance with the minimum of a corresponding local forward cost function value and a corresponding local backward cost function value.

68. The method of claim 67, wherein step (c) further comprises the step of:

(5) generating a plurality of range values from said plurality of local differential blur spreads, wherein each range value corresponds to an image pixel location.

69. The method of claim 3, wherein step (e) comprises the step of time-delayed focussing the focussed camera, said focussed camera being located overhead a conveyor system downstream of said camera used to generate said first image and said camera used to generate said second image.

70. The apparatus of claim 17, wherein means (c) comprises:

(1) means for generating an initial differential blur spread in accordance with said first and second images; and

(2) means for performing a recursive relaxation procedure in accordance with said first and second images and said initial differential blur spread to generate an improved differential blur spread.

71. The apparatus of claim 17, wherein means (c) comprises:

(1) means for generating a 2N point discrete Fourier transform of said first image;

(2) means for generating a 2N point discrete Fourier transform of said second image;

(3) means for generating an initial gain and an initial differential blur spread in accordance with said 2N point discrete Fourier transforms of said first and second images;

(4) means for generating the discrete Fourier transform of a time-varying regularization vector in accordance with said initial gain and said initial differential blur spread;

(5) means for generating the discrete Fourier transform of the differential impulse response between said camera (a) and said camera means (b) in accordance with said discrete Fourier transformed time-varying regularization vector;

(6) means for updating said initial gain and said initial differential blur spread in accordance with said discrete Fourier transformed differential impulse response;

(7) means for generating a squared error in accordance with said discrete Fourier transformed differential impulse response, said updated gain, and said updated differential blur spread;

(8) means for testing for the convergence of said squared error; and

(9) means for repeating the operations of means (c)(4) through (c)(7), in accordance with said testing of means (c)(8), using said updated gain and said updated differential blur spread.

72. The apparatus of claim 71, wherein means (c)(4) employs a gaussian blur model.

73. The apparatus of claim 71, wherein means (c)(4) employs a cylindrical sinc blur model.

74. The apparatus of claim 17, where means (c) comprises:

(1) means for setting an initial differential blur spread equal to 1.0;

(2) means for performing a forward pass through said first and second images to generate a plurality of forward differential blur spreads and a plurality of forward cost function values using local recursive parameter adaption in the spatial domain;

(3) means for performing a backward pass through said first and second images, starting where the forward pass ended, to generate a plurality of backward differential blur spreads and a plurality of backward cost function values using local recursive parameter adaption in the spatial domain; and

(4) means for selecting a plurality of local differential blur spreads corresponding to a plurality of image pixel locations, whereby each local differential blur spread is selected from a corresponding local forward differential blur spread and a corresponding local backward differential blur spread in accordance with the minimum of a corresponding local forward cost function value and a corresponding local backward cost function value.

75. The apparatus of claim 74, wherein means (c) further comprises:

(5) means for generating a plurality of range values from said plurality of local differential blur spreads, wherein each range value corresponds to an image pixel location.

76. The apparatus of claim 19, wherein means (e) comprises the means for time-delayed focussing the focussed camera, said focussed camera being located overhead a conveyor system downstream of said camera used to generate said first image and said camera used to generate said second image.

77. The method of claim 1, wherein step (a) further comprises the step of:

(1) generating a calibration mapping corresponding to a plurality of test differential blur spreads and a plurality of test range values.

78. The method of claim 77, wherein step (a)(1) comprises the steps of:

(A) providing a test object corresponding to a test range value;

(B) generating a test image corresponding to said test object;

(C) generating a test differential blur spread corresponding to said test image;

(D) repeating steps (a)(1)(A) through (a)(1)(C) for a plurality of test range values to generate a plurality of test differential blur spreads; and

(E) generating said calibration mapping by minimizing a cost function in accordance with said plurality of test range values and said plurality of test differential blur spreads.

79. The method of claim 3, wherein step (a) further comprises the step of:

(1) generating a calibration mapping corresponding to a plurality of test differential blur spreads and a plurality of test range values.

80. The method of claim 79, wherein step (a)(1) comprises the steps of:

(A) generating a first test image corresponding to a test object using said camera having said first camera parameter;

(B) generating a second test image corresponding to said test object using said camera having said second camera parameter;

(C) generating a test differential blur spread corresponding to said first and second test images;

(D) generating a third test image with a test focussing camera, said third test image corresponding to said test differential blur spread;

(E) determining a test focus distance corresponding to said test focussing camera during step (a)(1)(D);

(F) repeating steps (a)(1)(A) through (a)(1)(E) for a plurality of test differential blur spreads; and

(G) generating said calibration mapping by minimizing a cost function in accordance with said plural-

ity of test differential blur spreads and said plurality of test focus distances.

81. The apparatus of claim 17, wherein means (c) comprises means for generating a calibration mapping corresponding to a plurality of test differential blur spreads and a plurality of test range values.

82. The apparatus of claim 81, wherein means (c) comprises:

(1) test camera means for generating a plurality of test images corresponding to a plurality of test objects corresponding to said plurality of test range values;

(2) means for generating said plurality of test differential blur spreads corresponding to said plurality of test images; and

(3) means for generating said calibration mapping by minimizing a cost function in accordance with said plurality of test range values and said plurality of test differential blur spreads.

83. The apparatus of claim 19, further comprising:

(f) means for generating a calibration mapping corresponding to a plurality of test differential blur spreads and a plurality of test focus distances.

84. The apparatus of claim 83, wherein means (f) comprises:

(1) test camera means, having said first camera parameter, for generating a plurality of first test images corresponding to a test object;

(2) test camera means, having said second camera parameter, for generating a plurality of second test images corresponding to said test object;

(3) means for generating said plurality of test differential blur spreads corresponding to said pluralities of first and second test images;

(4) a test focussing camera for generating a plurality of third test images, said plurality of third test images corresponding to said plurality of test differential blur spreads;

(5) means for determining said plurality of test focus distances corresponding to said test focussing camera; and

(6) means for generating said calibration mapping by minimizing a cost function in accordance with said plurality of test differential blur spreads and said plurality of test focus distances.

85. An apparatus for determining a differential blur spread corresponding to object, comprising:

(a) camera means, having a first camera parameter, for providing a first image of said object;

(b) camera means, having a second camera parameter, or providing a second image of said object, said second camera parameter being different from said first camera parameter;

(c) means for performing a relaxation procedure in accordance with said first and second images to generate said differential blur spread;

(d) means for determining a range of said object in accordance with said differential blur spread; and

(e) means for focussing a camera in accordance with said range.

86. The apparatus of claim 85, wherein said object is a package on a conveyor system and said camera is a high-resolution camera positioned overhead said conveyor system to generate images used to read a label on said package.

87. The apparatus of claim 85, wherein means (e) comprises the means for time-delayed focussing the focussed camera, said focussed camera being located overhead a conveyor system downstream of said camera used to generate said first image and said camera used to generate said second image.

88. The apparatus of claim 85, further comprising:

(f) means for generating a calibration mapping corresponding to a plurality of test differential blur spreads and a plurality of test focus distances.

89. The apparatus of claim 88, wherein means (f) comprises:

(1) test camera means, having said first camera parameter, for generating a plurality of first test images corresponding to a test object;

(2) test camera means, having said second camera parameter, for generating a plurality of second test images corresponding to said test object;

(3) means for generating said plurality of test differential blur spreads corresponding to said pluralities of first and second test images;

(4) a test focussing camera for generating a plurality of third test images, said plurality of third test images corresponding to said plurality of test differential blur spreads;

(5) means for determining said plurality of test focus distances corresponding to said test focussing camera; and

(6) means for generating said calibration mapping by minimizing a cost function in accordance with said plurality of test differential blur spreads and said plurality of test focus distances.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 5,365,597
DATED : November 15, 1994
INVENTOR(S) : Lee F. Holeva

It is certified that error appears in the above-indentified patent and that said Letters Patent is hereby corrected as shown below:

Column 8, line 58, insert

--where:

$$c_2 = \frac{K}{c_1}$$ --

Column 10, line 68, delete "$+\bar{u}(n)\bar{u}(n)$" and insert therefor --$+\bar{u}(n)\bar{u}^{t}(n)$--.

Signed and Sealed this

Seventh Day of November, 1995

Attest:

BRUCE LEHMAN

Attesting Officer

Commissioner of Patents and Trademarks